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Eight-hundred-year temperature variability from the Norwegian continental margin and the North Atlantic thermohaline circulation

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[1] Four cores raised from the eastern Norwegian Sea and adjacent Norwegian fjords at sites influenced by Atlantic water have been investigated. Oxygen isotope analyses in benthic and planktonic foraminifera are used as a proxy for the paleotemperature development spanning the last 800 years. The cores have been dated using a combination of ^{210}Pb and radiocarbon dates yielding time resolutions of 2–5 years for the last century and 9–25 years beyond this. The proxy records have been compared with instrumental time series covering the last 100 years in order to validate the oxygen isotope measurements as a proxy for paleotemperature. The comparison shows that the paleotemperature variability derived from the oxygen isotope analyses is generally similar to the amplitudes and trends seen in the instrumental time series. In particular, a cooling around 1905–1925 followed by a warming until 1955 is evident in all proxy records as well as in the instrumental time series. Beyond the last century the proxy records show two periods from ~1225–1450 and ~1650–1905(25) when temperatures were 1.3–1.6°C lower than present separated by a period of temperatures periodically comparable to present. The last 80 years represent the modern warming and appear to be the warmest period of the last 800 years. We find that that the ocean temperature variability is comparable to terrestrial reconstructions from the region implying a strong link in the ocean-atmosphere climate system. This suggests that the climate variability in this region beyond the period covered by instrumental time series was also associated with changes in the thermohaline circulation. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4267 Oceanography: General: Paleoceanography; 4512 Oceanography: Physical: Currents; 4870 Oceanography: Biological and Chemical: Stable isotopes; *KEYWORDS:* paleoceanography, last 800 years, stable isotopes

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1. Introduction

[2] Oceans represent important components of the climate system by transporting and redistributing heat and moisture globally. The transport of heat by the northward flow of the North Atlantic Current into the Nordic Sea region is of major importance for maintaining an exceptionally mild climate of NW Europe for its latitude. Variability in the temperature conditions in the North Atlantic Current on millennium-century timescale has previously been demonstrated from studies of marine cores from the Nordic Seas and the North Atlantic [e.g., *Bond et al.*, 1997; *Klitgaard-Kristensen et al.*, 2001; *Koc Karpuz and Jansen*, 1992; *Lehman and Keigwin*, 1992; *Risebrobakken et al.*, 2003]. In addition, more detailed information from the studies of long terrestrial instrumental time series and proxy records have revealed the complexity of the climate system in terms of spatial structure and its variability in amplitude and frequency over the last millennium. Even though the ocean circulation is an important component of the climate system detailed knowledge on the natural variability on centennial-decadal scale of this system over the last millennium is still sparse. Information from instrumental oceanic time series is limited, because sections monitored on a regular basis are few and time series derived from such observations span less than 100 years [*Schulz et al.*, 2002]. However, it is important to have long time series to resolve the inherently low-frequency variations typical for the ocean circulation changes. Investigations of marine proxy records are therefore essential in order to reconstruct ocean circulation variability on decadal-centennial time resolution beyond the last 100 years of the last millennium. Here we present results from a sequence of cores: one core from the eastern Norwegian Sea margin and three cores recovered from adjacent fjord basins (Figure 1). The time resolution of these records varies between 2 and 30 years enabling us to capture variability in paleotemperature that are comparable to the instrumental records. The locations of the marine records investigated in areas directly influenced by the North Atlantic

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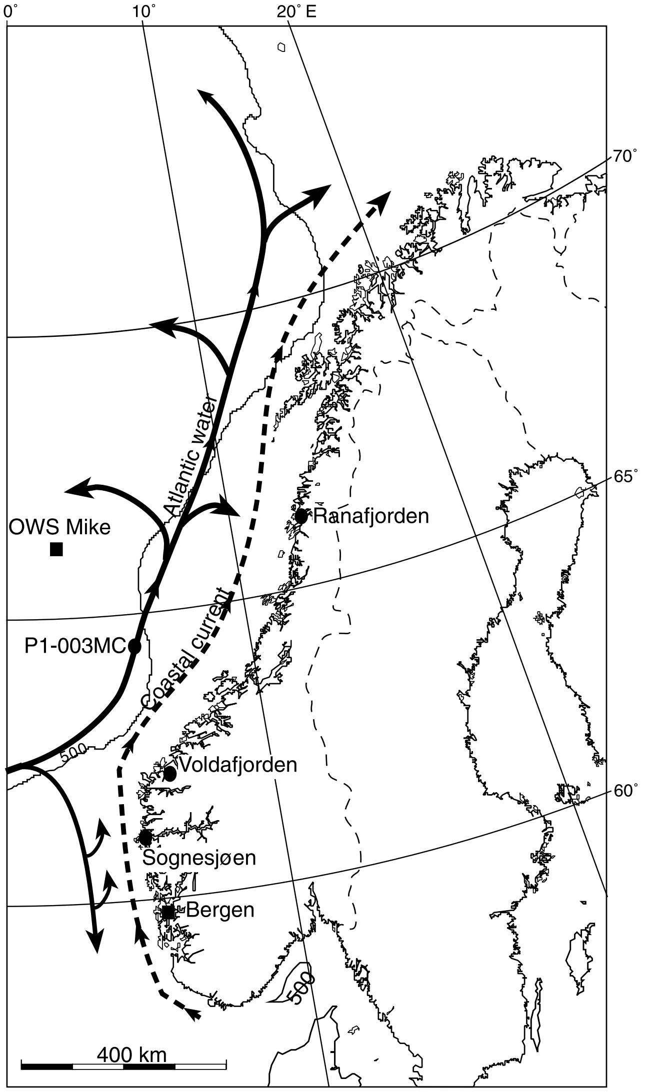

Figure 1. Main surface currents in the Norwegian Sea, the Norwegian Current, and the Norwegian Coastal Current. Locations of marine cores studied are indicated with black circles and sites with instrumental time series with black squares.

Current allow us to investigate centennial to multidecadal scale ocean circulation variability in the North Atlantic over the last eight centuries.

2. Material and Method

[3] Core P1-003MC (63°45.4N 05°15.2E), a 41.6 cm long multicore, was retrieved at 851 m water depth on the upper continental slope (Figure 1), located directly under the influence of the Norwegian Current (Figure 1) [*Berstad et al.*, 2003]. From western Norwegian fjords three cores have been studied (Figure 1). A gravity core, HB111-01GC (61°01.3N 04°48.4E) was retrieved at 464 m water depth in Sognesjøen (G. Mikalsen and H. P. Sejrup, A high-resolution 2500 year temperature record from Sognesjøen, western Norway; possible correlations to atmospheric delta14C cycles, submitted to *The Holocene*, 2003, hereinafter referred to as Mikalsen and Sejrup, submitted manuscript, 2003). Only results from the upper 32 cm of the 292 cm long core are presented here. At 694 m water depth in Voldafjorden (Figure 1) a 25 cm long boxcore core, HM109-04BC (62°10.4N 05°58.3E), was taken. From Ranafjorden (Figure 1) a 31 cm long boxcore core, HM122-10BC (66°09.2N 12°39.4E), was retrieved from 307 m water depth.

[4] The cores were visually described during subsampling at 0.5 cm intervals, and samples sieved at 1 mm, 0.125 mm and 0.063 mm sieves for grain size distribution. The cores have been analyzed for content of $CaCO_3$ and total organic carbon (only cores HB111-01GC and HM122-10BC). All cores are characterized by homogenous sediment with silt and clay contributing with more than 95%.

[5] Micropaleontologic analyses of benthic foraminiferal content have been carried out on all cores, and for cores HM109-04, P1-003MC and HM122-10BC the content of dinoflagellates have been studied. These results will be reported elsewhere. In all cores oxygen isotope analyses on foraminifera were carried out. From P1-003MC $\sim$20 individuals of the planktonic species *Neogloboquadrina pachyderma* (right coiled) was picked from the 150 μm–1 mm fraction. In HB111-01GC and HM109-04BC 3–5 specimens of the benthic foraminifera *Uvigerina mediterranea* were picked, and in HM122-10BC 20–25 individuals of the benthic foraminifera *Cassidulina laevigata* from the 125 μm–1 mm fraction were used. The species used for oxygen isotopes analysis are assumed to calcify in equilibrium with seawater [*Shackleton*, 1974], except *C. laevigata* that has been reported to calcify 0.2‰ lighter [*Poole*, 1994]. The samples were measured at the GMS laboratory at University of Bergen. The reproducibility reported by the laboratory is 0.07‰ for $\delta^{18}O$, based on replicate measurements of carbonate standards. All results are reported as $\delta^{18}O$ in ‰ versus PBD, using NSB 19. Based on the $\delta^{18}O$ measurements relative temperature estimates can be deduced from the general relationship that a 0.26‰ shift in $\delta^{18}O$ values correspond to 1°C change for the North Atlantic [*Bemis et al.*, 1998; *Shackleton*, 1974].

[6] The chronology of the cores is based on a combination of ^{210}Pb and ^{137}Cesium that covers the last century and radiocarbon AMS dates for the older part of the cores (Table 1, Figure 2). The radiocarbon dates were calibrated using CALIB 4.3 using a radiocarbon reservoir age of 400 years [*Stuiver et al.*, 1998]. Based on the ^{210}Pb and ^{137}Ce content and using a CRS (Constant Rate of Supply)-model, ages were reconstructed for the upper part of each core. In all cores the ^{210}Pb and ^{137}Ce content showed a typical decrease with depth. The ages calculated based on ^{210}Pb and ^{137}Ce are shown in Figure 2. The ^{210}Pb and ^{137}Ce dating method has age uncertainties of 10–15%, with the uncertainty increasing in the oldest part of the record. The age-depth model for each core is shown in Figure 2. These indicate that the 0.5 cm sampling interval in the cores yield time resolutions of 2–9 years for the last 100 years and 9–25 years prior to that (Figure 2). The age uncertainty is about 100–140 years for the radiocarbon dates and hence,

Table 1. Radiocarbon Dates in the Investigated Cores

Location	Core	Depth, cm	Species or Stratigraphic Marker	Laboratory Reference	Conventional ^{14}C Age, Ka (ref 1950)	AMS ^{14}C Age, Reservoir Corrected, 400 Years	Calendar Age, years AD
Voldafjorden	HM109-04BC	23.5–24.0	foraminifera	ETH-23599	575±80	175±80	1283–1468
Ranafjorden	HM122-10BC	19–19.5	*B. skagerrakensis*	Tua-3350	680±60	280±60	1590–1695
	HM122-10BC	29.0–29.5	*Hyalinea balthica*	Tua-2824	1120±65	320±65	1255–1340
Norwegian margin	P1-003MC[a]	29.3–30.8	*N. pachyderma* (*dex*)	ETH-23213	750±55	350±55	1495–1644
		39.3–40.3	*N. pachyderma* (*dex*)	ETH-23214	930±75	530±75	1366–1470
Sognesjøen	HB11-01GC[b]	31–32	*B. skagerrakensis*				

[a] From *Berstad et al.* [2003].

[b] From Mikalsen and Sejrup (submitted manuscript, 2003).

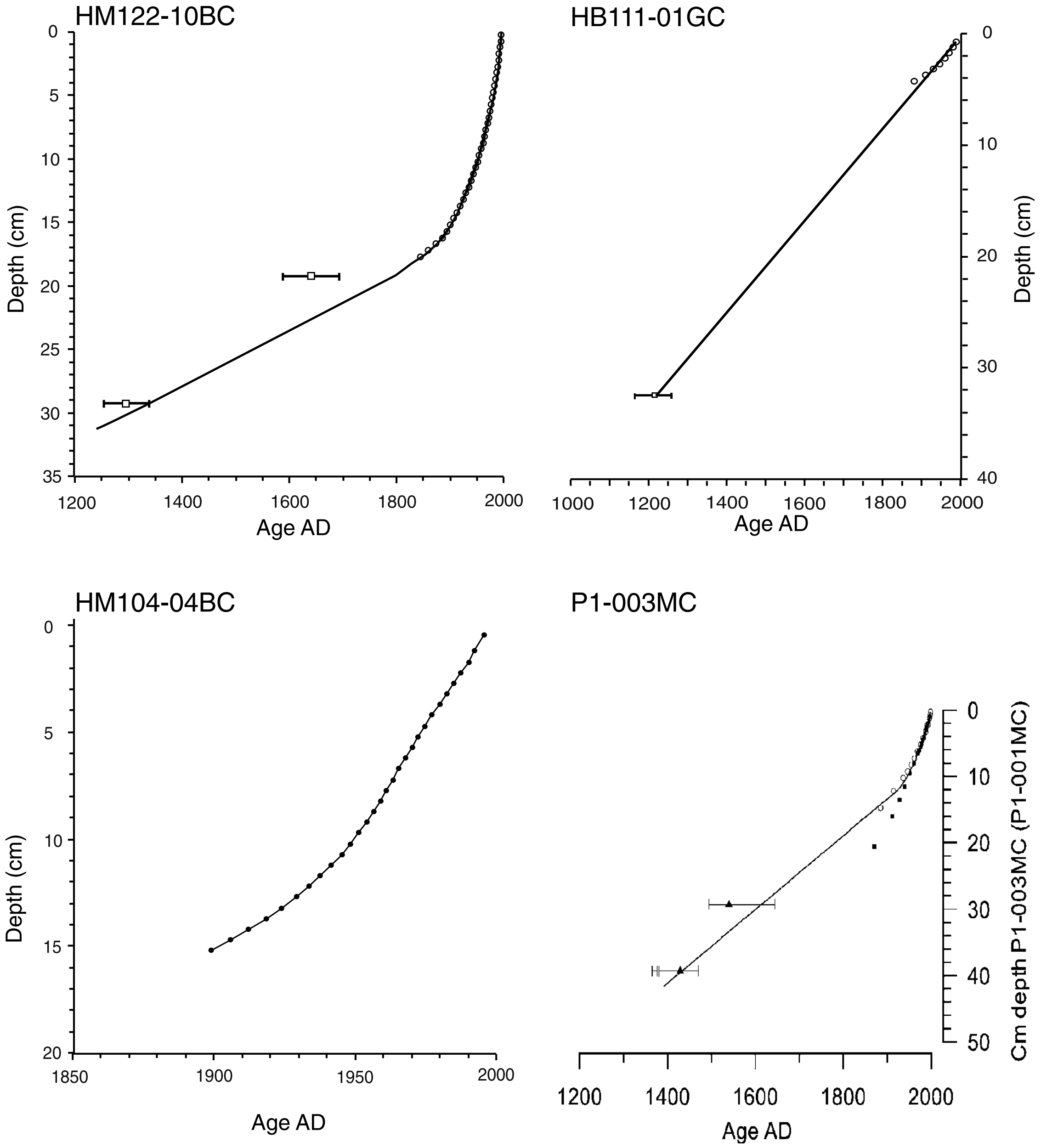

Figure 2. The age-depth models for each core presented in this study. The circles indicate ages obtained by ^{210}Pb and ^{137}Cs dating. Horizontal bars show radiocarbon dates with one standard deviation. Note that depth and age scales are different between the cores.

the timing of the climate events and changes for the period from 1300–1900 are governed by these chronologic uncertainties. This means that an event occurring at 1410 in one core will have an age uncertainty ranging from 1270–1550, which is important to bear in mind when comparing to other climate records. Slightly different approaches have been used in establishing the age-depth models (Figure 2). Longer cores have also been retrieved from all core localities and information on sedimentation rates from these have been used in evaluating and establishing the age-depth models for the short cores.

3. Fjords and Oceanographic Setting

[7] The general hydrographic circulation pattern in the Norwegian fjords is similar to an estuarine circulation pattern [*Gade and Edwards*, 1980] with three types of water masses prevailing. An upper layer, usually less than 20 m, of low and variable salinity surface waters that flows out of the fjord. This outflow creates a counter current that covers the water column between the upper brackish layer and down to the depth of the sill, referred to as the intermediate water. This water mass is a mixture of surface water and basin water and also influenced by the water from the coastal current flowing along the Norwegian Coast. Below the intermediate water masses the basins are filled with basin water exhibiting small seasonal variability and temperatures and salinities similar to the Atlantic Water on the shelf. The renewal of deep basin water is controlled by inflow from the shelf, internal diffusion processes in the fjord basins and the sill depth. The fjords investigated in this present study are characterized by deep sills (Voldafjorden 200 m, Ranafjorden 260 m and Sognesjøen 250 m) allowing for a direct connection between the basins in the fjords and the Atlantic Water prevailing on the shelf. The inflow of Atlantic water into the fjords has been demonstrated by comparing instrumental records from the open ocean region and the fjords. In Sognesjøen observations of salinity and temperature in bottom water at 300 m [*Aure and Østensen*, 1993] parallel the changes in the trends and absolute shifts of those properties in the sea surface in the adjacent Norwegian Sea (ocean weather ship station "Mike," 66°N 02°E) over the past 50 years [*Østerhus et al.*, 1996] (Figure 3). This demonstrates that the outer fjord basins can be used as valid monitors of changes in the Atlantic Water. Furthermore, valuable information on the variability of salinity and temperature can be obtained from the instrumental observations. In Sognesjøen, observations from 1935–2002 show salinity shifts between 34.9 and 35.2 and temperatures between 6 and 8.5°C with a seasonal temperature amplitude on the order of ~1.5°C between the winter and the summer months. Figure 3 also shows the variability of the annual air temperature from Bergen that is comparable to the variations seen in the ocean, indicating the link between the ocean-atmosphere system. The observed decadal climate changes over the past 60 years in the Norwegian Sea are to a large degree controlled be changes in the large-scale atmospheric circulation pattern reflecting the North Atlantic Oscillation, NAO [*Hurrell*, 1995] (Figure 3).

[8] The western Norwegian outer fjord basins have generally been subject to high-accumulation during the Holocene and the deglaciation with sediments thickness varying from a few meters and in some places up to 2–300 m [*Sejrup et al.*, 1996]. For the youngest part of Holocene sedimentation rates of 30–60 cm/kyr have been estimated by radiocarbon dating of long marine cores retrieved at the same localities at those sites investigated in this study (Figure 2) and other fjord sites [*Mikalsen et al.*, 2001; *Sejrup et al.*, 2001; Mikalsen and Sejrup, submitted manuscript, 2003; A. Lyså et al., The late glacial—Holocene seismic stratigraphy and sedimentary environment in Ranafjorden, northern Norway, submitted to *Marine Geology*, 2003].

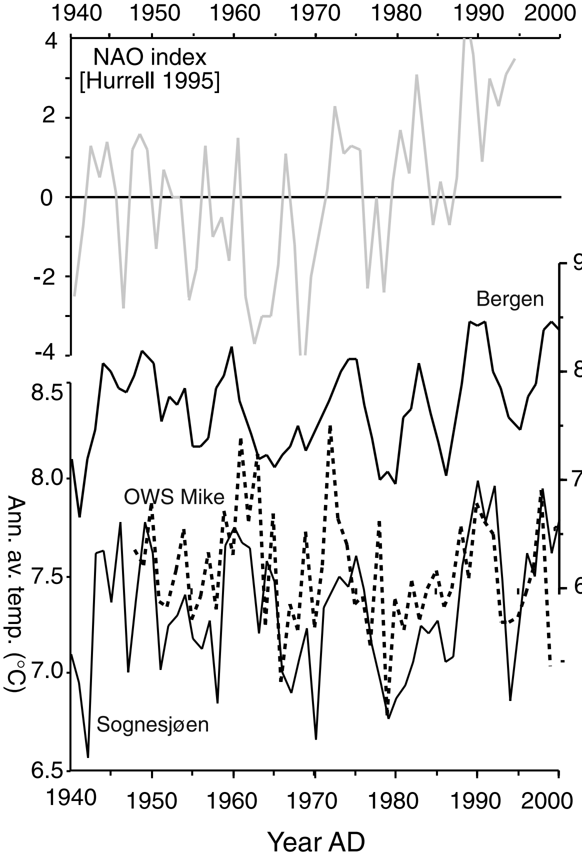

Figure 3. Annual temperatures for the last 60 years measured at ocean weather station "Mike," Norwegian Sea [*Østerhus et al.*, 1996], at 300 m water depth in Sognesjøen [*Aure and Østensen*, 1993], and annual air temperature from Bergen (3 year running mean) [*Nordli*, 1997] (for locations, see Figure 1). The winter NAO index [*Hurrell*, 1995] is shown for comparison with the instrumental time series for the last 60 years.

4. Marine Oxygen Isotope Values as Indicators of Paleotemperature

[9] The δ^{18}O benthic foraminiferal records from the two fjords, Ranafjord and Voldafjord, and the δ^{18}O planktonic foraminiferal in the core from the Norwegian margin spanning the last 100 years are shown in Figure 4. In the

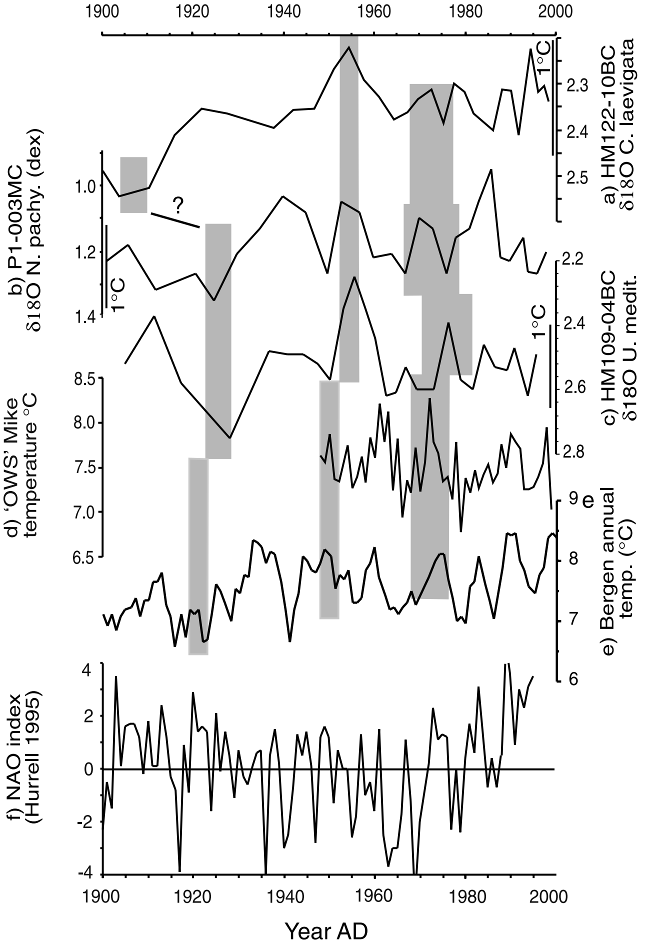

Figure 4. Stable oxygen isotope changes over the past 100 years in the cores from (a) HM122-10BC (Ranafjorden), (b) P1-003MC (Norwegian Margin), and (c) HM109-04BC (Voldafjorden). Instrumental time series of (d) annual sea temperature from 10–100 m water depth at "OWS" Mike [*Østerhus et al.*, 1996], (e) annual air temperature from Bergen (3 year running mean) [*Nordli*, 1997], and (f) NAO index from [*Hurrell*, 1995]. Shaded rectangles indicate temperature shifts regarded as similar in proxy and instrumental records. The chronology of the marine cores is based on ^{210}Pb dating.

two southern δ^{18}O records of the past 100 years the most noticeable feature seen are the heavy values in the oxygen isotopes around 1925 whereas the heaviest values in the δ^{18}O record from Ranafjorden is recorded around 1905 (Figure 4). After 1910–1930 the oxygen isotope values decrease and culminate with light values at around 1955 that can be recognized in all records. Assuming that only these changes in the oxygen isotope records reflect shifts in temperature this would correspond to a temperature increase of 1.2–1.6°C. After 1955 the fluctuations in the oxygen isotope records show amplitudes varying from 0.15–0.2‰ that would indicate temperature variations of about 0.6–0.8°C, but with little or no underlying trend.

[10] The isotopic signal may in addition to the temperature changes, however also reflect changes in salinity. If the oxygen isotopic changes of 0.3–0.6‰ we find over the last 100 years were caused by salinity variations, this would correspond to a salinity change of more than 1–2 psu. Such large salinity changes appear unrealistic in the study area as the instrumental measurements of salinity over the past 50 years show maximum amplitude of 0.3 psu [*Aure and Østensen*, 1993; *Blindheim et al.*, 2000]. We therefore rule out that salinity variations as the main cause of the shifts recorded in the oxygen isotope values, and suggest that the changes in the oxygen isotopic records from the Norwegian margin primarily reflect temperature variations in the Atlantic Water flowing into the Norwegian Sea.

[11] In order to evaluate the reliability of the paleorecords we have compared these with instrumental time series that reflects the regional climate development. The time series are from Bergen showing annual air temperature during the past 100 years [*Nordli*, 1997] and annual upper ocean temperature from "OWS" Mike (Figure 1) in the Norwegian Sea over the past 50 years [*Østerhus et al.*, 1996] (Figure 4). The instrumental time series displaying the temperature variability on annually time resolution prohibits a peak to peak correlation with the paleorecords due to the lower time resolution in these. However, the variations in the trends and the absolute temperature ranges can be compared between the records. In general, we find that the main trends in the temperature variability in the instrumental time series can be recognized in the paleorecords (Figure 4). In particular, the cold period around 1925 in the oxygen isotope records from the southern Norwegian Sea is simultaneously with the coldest temperatures recorded in Bergen of the last 100 years (Figure 4). The strongest cooling in the northern core (HM122-10BC) is recorded around 1905, hence occurring somewhat earlier in the north than in the south. These cold periods may not be simultaneously but provided the age uncertainties and time resolution a more precise correlation of these cold periods is not possible. The subsequent supposed warming trend from 1910–1930 to 1955 found in the oxygen isotope records corresponds to around 1°C, occurs at the same time as temperature increases by 2°C in Bergen. The temperature amplitude of between 0.6 and 0.8°C after 1955 deduced from the oxygen isotope records is similar to the measured range of ~1°C at "OWS" Mike where temperatures vary between 7.3 and 8.3°C for the last 50 years (Figure 4). This suggests that the oxygen isotope records reasonably reflect the amplitude of the ocean temperature variability. Despite the problems governed each age-depth model, the overall similarity of the temperature ranges, amplitudes and the trends between the proxy records and the instrumental time series suggests that the δ^{18}O records mainly reflect ocean temperature variations. Furthermore, only small salinity has been observed over the same time indicating that these, at most, plays a minor role. This also provides confidence that the marine oxygen isotope records are capable of reproducing the ocean paleotemperature development satisfactory.

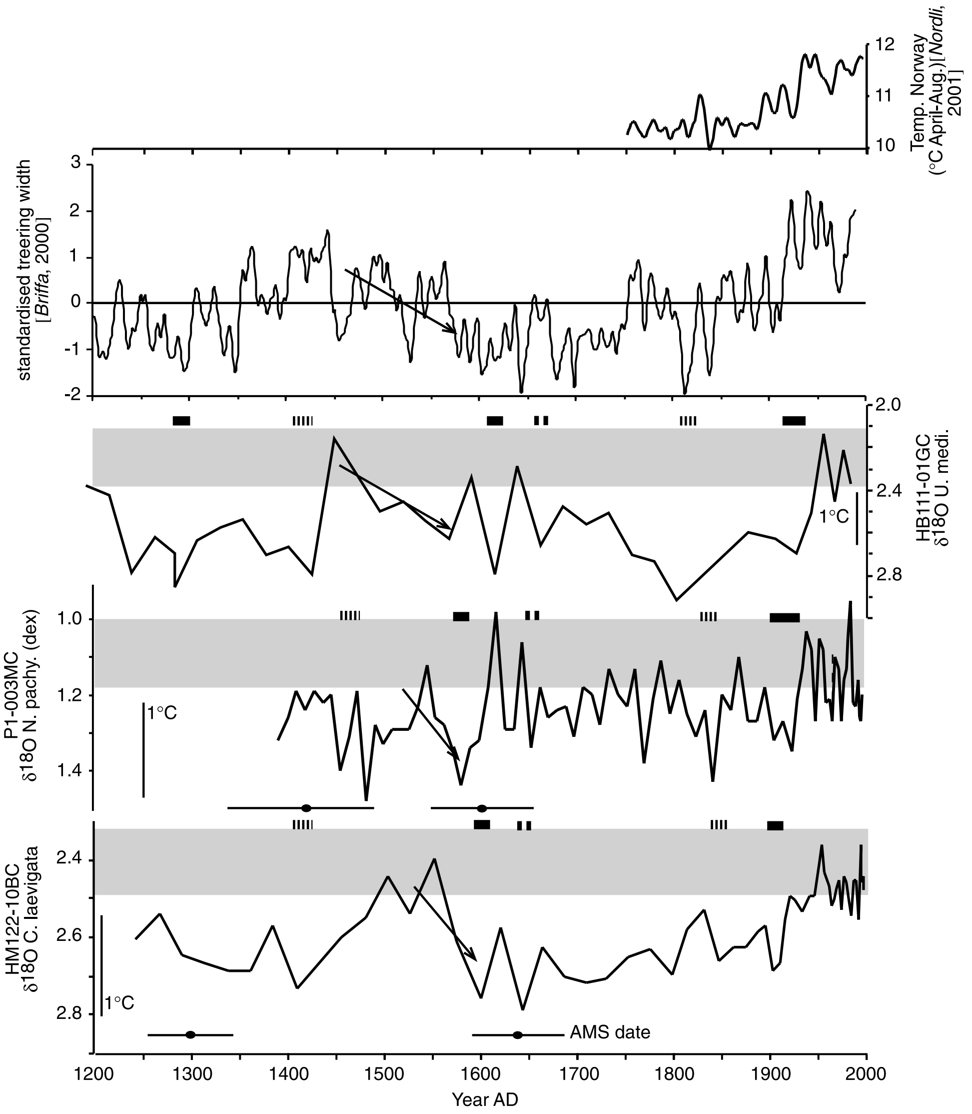

Figure 5. The three lowest panels show stable oxygen isotope in the cores HM122-10BC (Ranafjorden), P1-003MC (Norwegian margin) and HB111-01GC (Sognesjøen) during the past 800 years. These are compared to historical temperature data (10 year filter) reconstructed from eastern part of southern Norway [*Nordli*, 2001] and tree ring data from northern Scandinavia [*Briffa*, 2000] shown in the top two panels. A relative temperature scale is indicated for oxygen isotope record. Shaded horizontal rectangles indicate temperatures comparable to present for the δ^{18}O records. The short different bars show short cooling periods that are regarded as occurring at approximately the same time. Circles with one standard deviation indicate AMS dates. Arrows show the cooling trend from 1500 to 1600.

[12] For the last century the time resolution in the marine cores presented reveals climate changes on decadal scale (Figure 4). In the north Atlantic decadal scale climate variability has been closely linked to changes in the large-scale atmospheric circulation pattern reflecting the North Atlantic Oscillation, NAO [*Hurrell*, 1995]. The similarity between the climate changes seen in the oxygen isotope records and the instrumental time series over the past century indicates that these probably occur, in large parts, as a result of changes in the NAO (Figure 4). The decreasing time resolution in the marine records due to the compaction of the sediments, however, prevents detailed comparison to the NAO reconstructions [e.g., *Luterbacher et al.*, 2002] prior to the last century.

5. Ocean Circulation Changes During the Last 800 Years in the Norwegian Sea

[13] The δ^{18}O benthic foraminiferal records from the two fjords, Ranafjord and Sognesjøen, and the δ^{18}O planktonic foraminiferal in the core from the Norwegian margin spanning the last 800 years are shown in Figure 5. The most outstanding of δ^{18}O foraminiferal records is the light values occurring at the beginning of the early 20th century

and throughout the past ~80 years representing the modern warming, corresponding to 1–1.3°C temperature increase. The past 80 years show the highest temperatures of the past 800 years. Prior to this the most common features of the three oxygen isotope records include three major climate time intervals occurring from ~1225–1450, 1450–1650, 1650–1905(25) (Figure 5) taking into account the differences in time resolution between the records and the uncertainties related to the chronologies. The timing of these periods is associated with uncertainties of about 100 years for the last millennium. Temperatures decreased ~1°C at around 1225 and remained low compared to present until 1450 (Figure 5). After ~1450 temperatures increased by ~1.2°C followed by high amplitudinal flickering of temperatures periodically reaching temperatures comparable to present until 1650. Between 1650 and 1910–1920 temperatures are generally colder compared to present in all the records. But the core located at the margin, having the highest time resolution, also displays short periods of temperatures comparable to present conditions from 1650–1900. In Ranafjord the core exhibits a more gradual temperature increases toward 1900. Superimposed on the major centennial climate trends all three records exhibit climate variability on multidecadal scale with numerous short-lived (<100 years) periods of colder or warmer temperatures with temperature changes of ~1°C (Figure 5). However, the occurrences of these are highly dependent on sampling resolution and the timing on the age-depth models, hence they can not at this stage be regarded as significant.

[14] The overall resemblance between our marine records indicates that regional climatic changes are being recorded and these reflect alterations in the inflow of Atlantic water into the Nordic Seas during the past 800 years. Furthermore, the overall temperature trends seen in the $\delta^{18}O$ are comparable both to tree ring data from northern Scandinavia extending back to 1200 [*Briffa*, 2000], and instrumental time series based on historical and harvest data from farms in eastern Norway [*Nordli*, 2001]. This further implies a relationship between the ocean-atmosphere system beyond the extent of the instrumental time series.

6. Regional Climate Implications and Discussion

[15] From the marine realm there are only few other marine records with similar time resolution that can be compared with our records. In the Norwegian Sea SST reconstructions from contents of diatoms and planktonic foraminifera show a 1.5°C cooling from 1400, a slight increase in temperature at 1700 followed by a renewed warming at 1930 [*Koc and Jansen*, 2002; *Andersson et al.*, 2003]. In a core from the Skagerrak the coarsening of sediments is attributed to increased storminess that started at 1350 and terminated at 1900 interspersed with lesser storminess from 1550–1750 [*Hass*, 1996]. The content of benthic foraminifera in a core from Nansen fjord, Greenland, on the western side of the Nordic Seas, indicates less influence of Atlantic Water at 1200, with a low around 1370 [*Jennings and Weiner*, 1996]. This was followed by enhanced Atlantic Water inflow at 1470, and subsequently reduced influence until 1905 [*Jennings and Weiner*, 1996]. Outside the Nordic Seas, *Cronin et al.* [2003] measured Mg/Ca in ostracods in a core from Chesapeake Bay and found overall cold conditions from ~1400–1900 corresponding to the "Little Ice Age," LIA. In combination with our proxy records, all these marine records exhibit overall similar trends in the temperature conditions with the onset of colder conditions at ~1200–1400 that prevailed, although not continuously, until 1900. In the Labrador Sea and in adjacent basins various studies by *Keigwin* [1996], *Keigwin and Pickart* [1999] and *Keigwin et al.* [2003] have demonstrated similar cold periods from ~1400–1900 but also exceptions to this. At the Laurentian Fan, *Keigwin and Pickart* [1999] found warmer SST′ based on planktonic foraminifera from 16th–19th century. This indicates that climate varied spatially in the North Atlantic region during the LIA, taking into account age uncertainty and time resolution among the marine records.

[16] The cold spells seen in our marine records in the 13th century are similar in timing to major ice advances in the mountain areas in the Alps, that was initiated at the beginning of the 13th century [*Grove*, 2001]. *Grove* [2001] relates this to the LIA, when the ice advanced and varied in extent until 1900 when larger retreats took place [*Grove*, 2001].

[17] Our findings demonstrate that the alterations in the oceanic temperature of the Atlantic Water are comparable in time to terrestrial climate trends in the North Atlantic region implying that large-scale ocean-atmospheric circulation changes were involved in shaping the climate variability on centennial timescale. Such variations have been attributed by changes in the strength of the thermohaline circulation [*Broecker*, 1991; *Lehman and Keigwin*, 1992; *Bond et al.*, 1997; *Cronin et al.*, 2003]. Previous studies have demonstrated that changes in NADW are associated with concurrent shifts in the ocean surface waters [*Lehman and Keigwin*, 1992; *Oppo et al.*, 2003], implying that shifts recorded in the surface water, i.e., Atlantic Water, could occur as a result of changes in the thermohaline circulation. Our results from the Norwegian Sea monitoring variations in the temperature conditions of the Atlantic Water therefore suggest that the cooling in the beginning of the 13th century could be associated with a reduction in the strength of the thermohaline circulation. This probably remained reduced for several centuries and did not intensified to present levels before 1910–1920, although some recovery might have occurred around the middle of the millennium. Evidence from other studies in the North Atlantic has also revealed possible reductions of the thermohaline circulation in connection to the LIA. Studies on granulometric data from core P1-003MC, at the Norwegian margin, show that from ~1400–1700 the content of coarse-grained material (fine sand) was higher [*Berstad et al.*, 2003]. This coarsening is interpreted as a result of reorganizations of the ocean circulation in the Norwegian Sea probably related to a weakening of thermohaline circulation [*Berstad et al.*, 2003]. Furthermore, *Bianchi and McCave* [1999] studied variability in the sortable silt component in a deep-sea core from the North Atlantic and found that flux of overflow water at the Iceland-Scotland ridge decreased between

~1300–1450 and 1500–1700. Taken together these results support the evidence that THC was reduced from 13th–14th century probably corresponding to the initial part of the LIA when glaciers started advancing in the Alps [*Grove*, 2001]. *Broecker et al.* [1999] found in the southern Ocean, by the use of geochemical tracers of deep water, that high rates of southern ocean deep water were produced at the beginning of the LIA, here dated to the 13th century. Increased production of southern ocean deep water is to be expected when reductions are found in the North Atlantic as depicted in the proposed bipolar see-saw effect between the northern and southern hemispheres [*Stocker*, 1998]. Hence there is increasing evidence suggesting that the strength of the THC was reduced in the period ~1300–1700, although the precise timing of this is limited by the uncertainties associated with dating these type of sediments.

7. Conclusions

[18] The investigations of four high resolution marine cores covering the last 800 years located in the eastern Norwegian Sea and fjords under the inflow of Atlantic Water into the Nordic Seas have revealed that:

[19] The similarity in trends and amplitudes between the oxygen isotope records and available instrumental temperature time series suggests that the proxy records reflect temperature variability in the Atlantic Water. This similarity further provides confidence that the oxygen isotope records are reliable in reconstructing paleotemperatures beyond the last century. Salinity variations cannot be excluded but are probably of minor importance since the observed are much smaller than what can be estimated from the oxygen isotopic changes.

[20] The most prolonged period of high temperatures is the last 80 years of the last 800 years. Beyond the last century the oxygen isotope records show two periods from ~1225–1450 and ~1650–1905(25) where temperatures are 1.3–1.6°C lower than present. From ~1450–1650 temperatures are periodically comparable to present.

[21] We find that the temperature changes over the last 800 years occur simultaneously with climate shifts recognized in terrestrial temperature reconstructions around the North Atlantic implying large-scale reorganizations of the ocean-atmosphere system are involved. We suggest that the cooling starting around 1300 was associated with a reduction in the strength of the thermohaline circulation that probably continued until 1700, although with some recovery, encompassing parts of the LIA.

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